

## Artificial FeCu(100) epitaxial ordered alloy films: Element-selective magnetic properties

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Epitaxial artificial FeCu alloy thin films in the fcc  $L1_0$  ordered phase were prepared by pulsed laser deposition on Cu(100). Magnetic circular dichroism in x-ray absorption at the Fe and Cu  $L_{2,3}$  edges was used to study the electronic and magnetic properties of the normally immiscible FeCu(100) alloy films. The Fe exhibits magnetic moments comparable to that of fcc Fe films, ruling out the occurrence of nonmagnetic fcc Fe. The ratio between orbital and spin contribution to the Fe  $d$  moments is significantly enhanced in FeCu with respect to Fe/Cu(100), and amounts to  $\approx 0.12$ . An induced magnetic moment of the Cu atoms is observed, which carries about 7% of the total  $d$ -band moment of the FeCu film. © 1998 American Institute of Physics. [S0021-8979(98)48011-3]

Magnetic artificial alloys have not yet been subject to investigations concerning their element-selective magnetic properties. Artificial alloys of the otherwise immiscible elements Fe and Cu have been synthesized mechanically in the bulk by ball milling techniques<sup>1,2</sup> as well as by sputtering.<sup>3,4</sup> It was reported that for Fe concentrations below  $\approx 70\%$  the fcc structure is assumed, and for higher Fe concentrations the bcc structure.<sup>2,3</sup> In contrast to these techniques we use pulsed laser deposition to stabilize the fcc phase of epitaxial artificial FeCu alloy thin films on Cu(100). The films grow in a layer-by-layer mode already starting with the first layer, as judged by reflection high energy electron diffraction during growth.<sup>5</sup> Subsequent deposition of monoatomic layers of Fe and Cu results in the  $L1_0$  ordered phase of FeCu. These films exhibit an easy axis of magnetization in the film plane.<sup>5</sup> Scanning tunneling microscopy investigations show a degree of layer perfection better than 98% per deposited FeCu bilayer.<sup>5</sup> Spin-resolved valence band photoemission measurements revealed bands which are present due to the reduced size of the alloy Brillouin zone perpendicular to the film plane.<sup>6</sup> This reflects the doubling of the unit cell in the ordered alloy with respect to pure Cu or Fe, and additionally proves the structural quality of our stacked samples.

In this contribution we report results of magnetic circular dichroism in soft x-ray absorption (XMCD) measurements of these fcc FeCu alloy films. XMCD probes the spin asymmetry of the unoccupied part of the band structure just above the Fermi level. The dichroism, i.e., the difference in absorption cross section upon reversal of the magnetization direction, depends on the transition probability for spin-up and spin-down electrons into the mainly minority type unoccupied bands, and constitutes an element selective measure of magnetic and electronic properties.<sup>7</sup> Sum rules<sup>8,9</sup> allow under some assumptions to extract the elementally resolved spin and orbital magnetic moments from the experimental absorption spectra.

Films of 10 atomic layers (monolayers, ML), alternately consisting of Fe and Cu, were deposited by pulsed laser

deposition at room temperature on a Cu(001) substrate. A cap layer of 3 ML Au was evaporated on top for protection against residual gases. After preparation of the samples, which was done at the laboratory in Halle, the samples were transferred under ultrahigh vacuum (UHV) conditions to the Berlin synchrotron radiation source (BESSY). During the transport a pressure of about  $4 \times 10^{-8}$  Pa was maintained in the transfer chamber. The typical time interval for transfer and transport elapsed between the preparation of the samples and the beginning of the measurements at BESSY was about 4 h.

XMCD measurements were performed at a sample temperature of 120 K. The sample was remanently magnetized along the in-plane [110] direction by ramping the current through a coil. The magnetization procedure was monitored by magneto-optical Kerr effect, as was the presence of the remanence before and after each scan of data acquisition.

Absorption spectra were taken at the PM-3 beamline at BESSY. The photon energy resolution was  $\approx 1.5$  eV in the region of the Fe and Cu  $L$  edges. Circularly polarized x rays were obtained by selecting light from 0.3 mrad below the ring orbit. Measurements of Co reference films yielded an estimate of about 40% for the degree of circular polarization in that configuration. The total electron yield was recorded by measuring the sample drain current with a bias voltage of  $-27$  V applied. The sample magnetization was reversed after each energy scan. The 8 or 10 scans at the Fe  $L$  edge, and between 40 and 60 at the Cu  $L$  edge were summed up. The spectra were normalized to the current of a gold grid monitor located just behind the exit slit of the monochromator, and corrected for the angle of light incidence of  $45^\circ$  and the estimated degree of circular polarization. The analysis of the Fe  $L_{2,3}$  absorption spectra was done as outlined in Ref. 10 or 11. In particular, the spectra were normalized to unity edge jump, and two step functions of 0.5 eV width and  $2/3(1/3)$  height at the  $L_3(L_2)$  absorption maxima were subtracted. A constant number of Fe  $3d$  holes of 3.34 was assumed.<sup>12</sup> The Cu  $L_{2,3}$  spectra were analyzed by comparing them to the spectra of Ref. 13, taking into account the different angle of incidence and the different degree of light polarization in our

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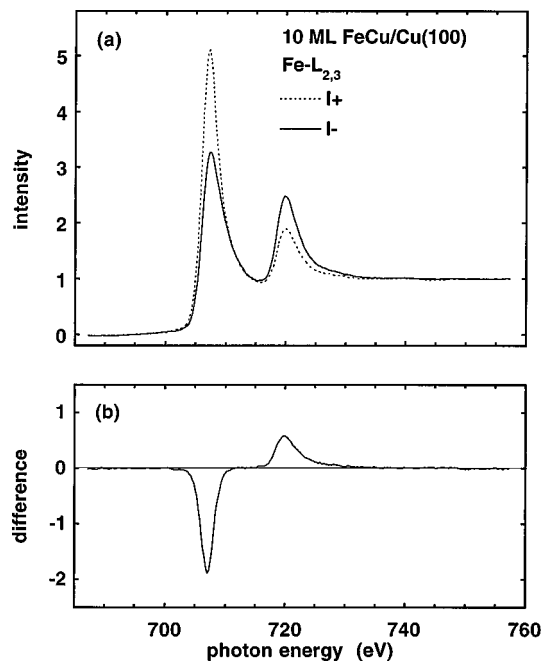


FIG. 1. (a) Absorption spectra at the Fe  $L_{2,3}$  edge of a 10 ML FeCu film for parallel (dotted line) and antiparallel alignment of magnetization direction and light helicity (solid line). (b) Difference between the spectra of (a).

experiment. In this way the value for the ratio of white line intensity to number of  $d$  holes for Cu of Ref. 13 is used, and it is not necessary to integrate the Cu absorption intensity.

Absorption spectra at the Fe- $L_{2,3}$  edge are shown in Fig. 1(a). Spectra for parallel and antiparallel alignment of magnetization direction and light helicity are reproduced by dotted and solid lines, respectively. The difference between the two spectra is plotted in Fig. 1(b). A strong dichroism is observed with negative (positive) peaks at the  $L_3$  ( $L_2$ ) edges. The sum rule analysis of the data yields a spin moment of  $1.8 \pm 0.06 \mu_B$ , and a ratio of orbital to spin moment of  $0.12 \pm 0.03$ .

Measurements under identical experimental conditions of 3.5 ML fcc Fe/5 ML Co/Cu(100) films, which are entirely ferromagnetically ordered,<sup>14</sup> resulted in a similar spin moment of  $1.9 \pm 0.1 \mu_B$ , and also in a similar (within 5%) white line intensity.<sup>6</sup> The cited errors represent the accuracy and reproducibility of the measurements, and do not include systematic errors due to uncertainties in the exact degree of circular polarization, the number of  $3d$  holes, or the details of the steplike background subtracted for white line integration. They are, however, appropriate for comparing results obtained from different samples under identical experimental conditions. Comparing the results from the FeCu alloy and the Fe/Co reference film, we conclude that all of the Fe atoms in the FeCu alloy film carry a moment close to that of fcc Fe. In the sum-rule analysis the contribution of the magnetic dipole term<sup>9</sup> to the spin moment is usually neglected, a variation of which may introduce an additional error of up to 10%.<sup>15</sup> The ratio  $\mu_L/\mu_S$  between the orbital and spin moment, nevertheless, is significantly enhanced in the FeCu film, being about a factor of 3 larger than in the 3.5 ML Fe film ( $0.04 \pm 0.01$ ).<sup>6</sup> Increased orbital moments have been ob-

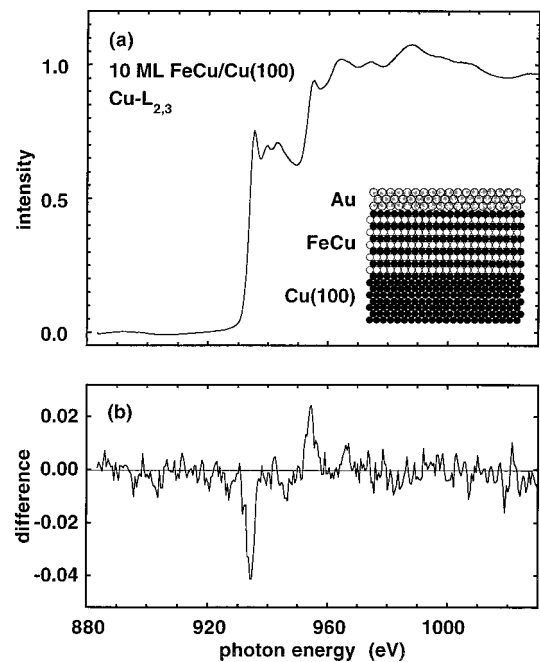


FIG. 2. (a) Absorption spectrum at the Cu  $L_{2,3}$  edge of a 10 ML FeCu film, averaged over antiparallel and parallel alignment of magnetization direction and light helicity. The inset shows a sketch of the film architecture. (b) Absorption difference between antiparallel and parallel alignment of magnetization direction and light helicity at the Cu  $L_{2,3}$  edge. Note the different vertical scale with respect to (a).

served previously in films of decreasing thickness,<sup>16</sup> and have been discussed in terms of higher density of states at the Fermi level,<sup>16,17</sup> and magnetic anisotropy.<sup>15,18</sup> We tentatively conclude the observed orbital moments as a consequence of the ordered layer stacking, reflecting the electronic structure of the FeCu films.

Figure 2(a) shows the absorption spectrum of FeCu at the Cu  $L_{2,3}$  edge. Here, the average absorption for both magnetization directions is reproduced rather than the individual curves, because the difference between these is much smaller than at the Fe  $L_{2,3}$  edge, and would not be reproduced clearly on the scale of Fig. 2(a). This is seen from Fig. 2(b), where analogously to Fig. 1(b) the difference in absorption between antiparallel and parallel alignment of magnetization direction and light helicity at the Cu  $L_{2,3}$  edge, corrected for the angle of light incidence and the estimated degree of circular polarization, is reported. Note the vertical scale, which is blown up by an (arbitrary) factor of 10 with respect to Fig. 2(a). A small but distinct dichroism at the energetic positions of the Cu  $L_3$  and  $L_2$  edges with the same sign as at the respective Fe edges is observed. It amounts to about  $-4\%$  and  $+2\%$  of the Cu edge jump height. A magnetic moment is thus present at the Cu atoms, introduced by the presence of the Fe atoms.

Applying the sum rules to the spectra of Fig. 2 yields Cu atomic spin moments of  $0.05 \pm 0.005 \mu_B$ . Before comparing this value to other systems, it has to be considered though that by measuring the absorption by the total electron yield there is still a significant contribution from the Cu(100) substrate to the Cu absorption signal at the thickness of the FeCu films (10 ML). For a mean free path of 11 ML ( $\approx 20 \text{ \AA}$ ) the Cu signal stems to about 55% from the substrate. Assuming

that the substrate atoms do not show any magnetic dichroism,  $\mu_S = 0.12 \pm 0.01 \mu_B$  is obtained for the Cu atoms in the FeCu film. Comparing that to the Fe atomic moment it is found that about 7% of the *d*-band magnetic moment of the FeCu film is carried by the Cu atoms.

The induced Cu magnetic moments are higher than those observed in Co/Cu multilayers ( $0.05 \mu_B$ )<sup>13,19</sup> or Fe/Cu multilayers (up to  $0.09 \mu_B$ , depending on the Cu layer thickness),<sup>19</sup> but comparable to Co<sub>90</sub>Cu<sub>10</sub> films ( $0.13 \mu_B$ ).<sup>13,19</sup> Theoretical calculations for Cu induced moments in Fe/Cu multilayers yielded values of 0.07,<sup>20</sup> 0.05,<sup>21</sup> and  $0.06 \mu_B$ .<sup>22</sup> For a layered FeCu alloy similar to the one investigated here the resulting theoretical moment was  $0.08 \mu_B$ .<sup>22</sup> This is slightly lower than what we observe experimentally, but has the right order of magnitude. It is conceivable that details in which the geometric structure assumed for the calculations differs from the structure realized in the FeCu samples may account for the differences between theory and experiment.

In conclusion, we have investigated ultrathin epitaxial fcc FeCu ordered alloy films on Cu(100). Element selective electronic and magnetic properties were obtained by XMCD at the Fe and Cu  $L_{2,3}$  edges. Induced moments of the Cu atoms, which amount to about 6% of that of the Fe moments, and increased Fe orbital moments were found. The findings are attributed to the modification of the electronic structure due to hybridization between Fe and Cu derived states, the reduced symmetry along the surface normal, and altered dimensionality in the layered alloys.

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